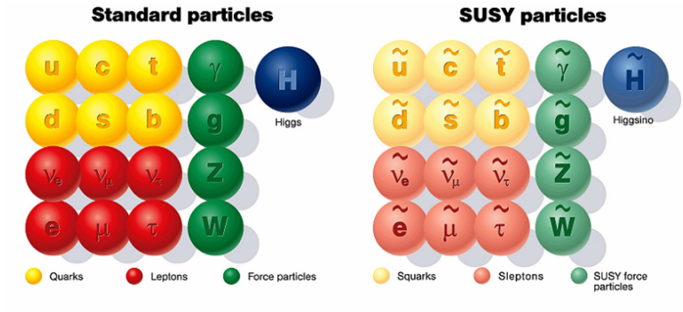
Whither[†] SUSY?

G. Ross, Sussex, October 2012

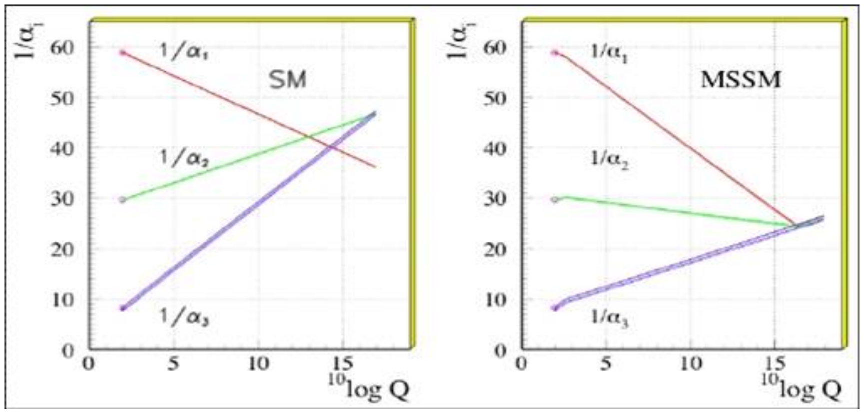
† **whither** *Archaic or poetic*
adv
1. to what place?
2. to what end or purpose?
conj
to whatever place, purpose, etc.
[Old English *hwider, hwæder;* related to Gothic *hvadrē;* modern English form influenced by HITHER]

Low energy

SUSY - to what end or purpose?



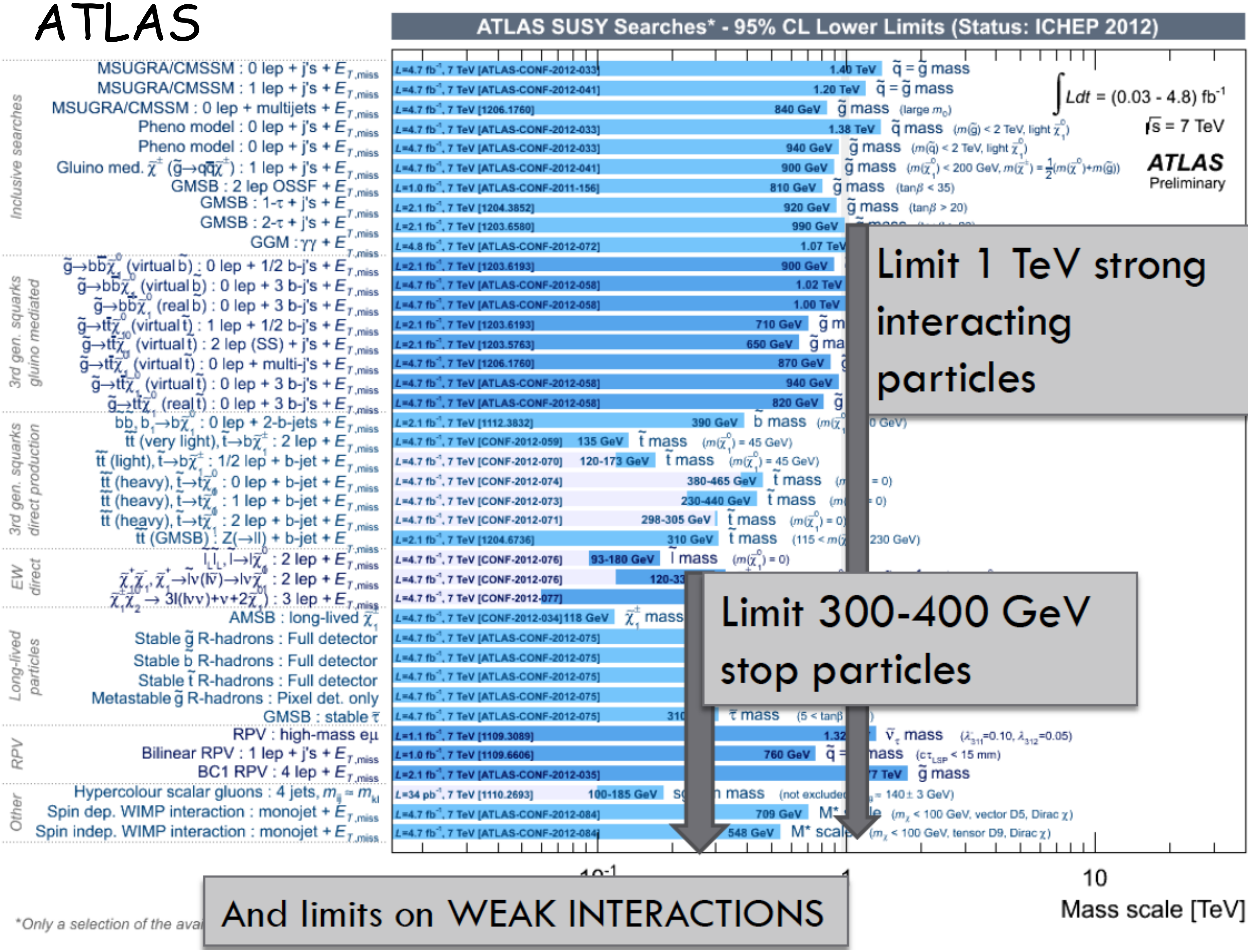
Unification: SU(5), SO(10),…



✔

The hierarchy problem: $M_{Higgs}, M_{W,Z} \ll M_{Planck}, M_{GUT}, ..$ ✔ (?)

ATLAS



ATLAS SUSY Searches* - 95% CL Lower Limits (Status: ICHEP 2012)
Limit 1 TeV strong interacting particles
Limit 300-400 GeV stop particles
And limits on WEAK INTERACTIONS
Mass scale [TeV]

SUSY - to what place?

breaking

Little hierarchy problem $\Rightarrow$ definite SUSY structure
^

MSSM:

105 +(19) Parameters

$$M_Z^2 = \sum_{\tilde{q},\tilde{l}} a_i \widetilde{m}_i^2 + \sum_{\tilde{g},\widetilde{W},\widetilde{B}} \widetilde{M}_i^2 + \ldots$$

$$m_{\tilde{q}} > 0.6 - 1 TeV \quad \Rightarrow \quad \Delta > a\frac{\widetilde{m}^2}{M_Z^2} \sim 100$$

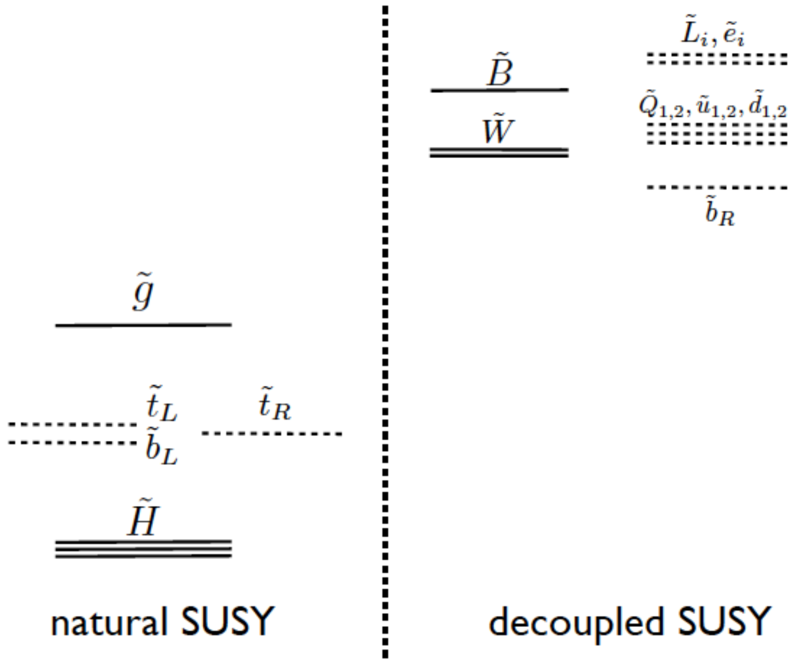
$\Rightarrow$ Correlations between SUSY breaking parameters and/or additional low-scale states

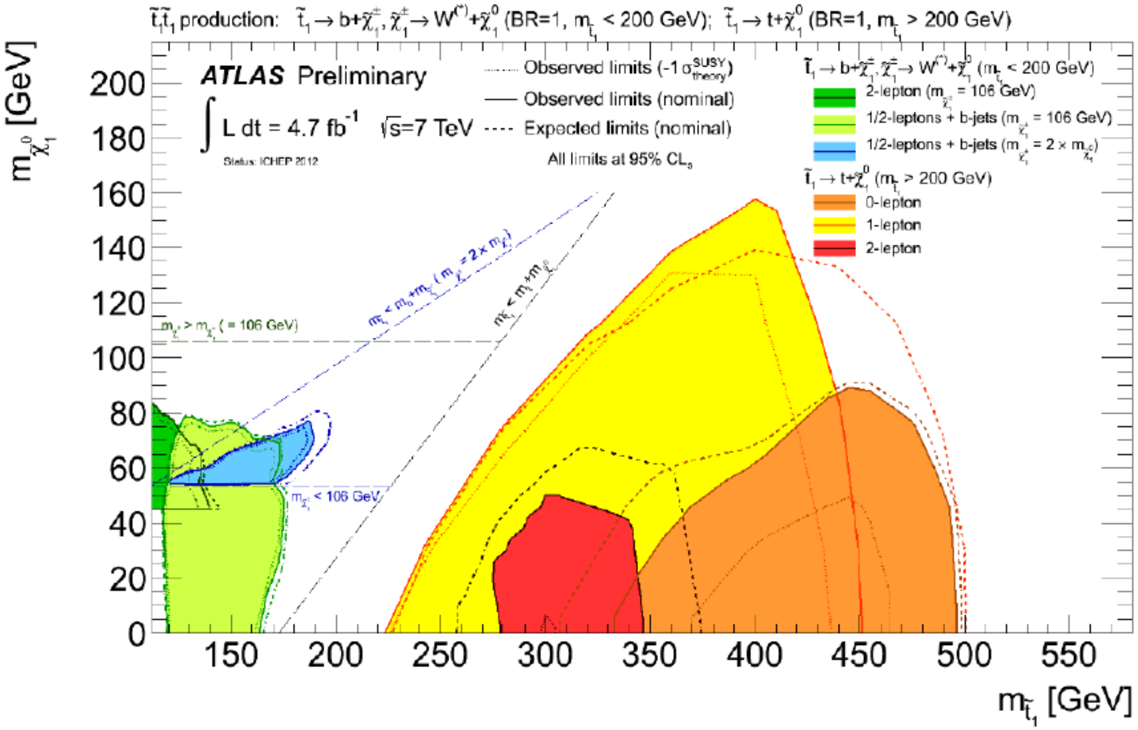
An exception: "Natural" SUSY

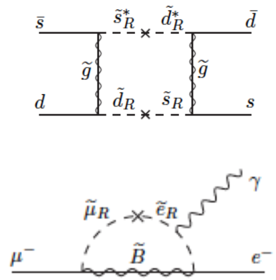
light stop $m_{\tilde{t},LHC} > 250\ GeV$

FCNC: 1,2 sgenerations heavy

Hierarchy problem: 3rd sgeneration light





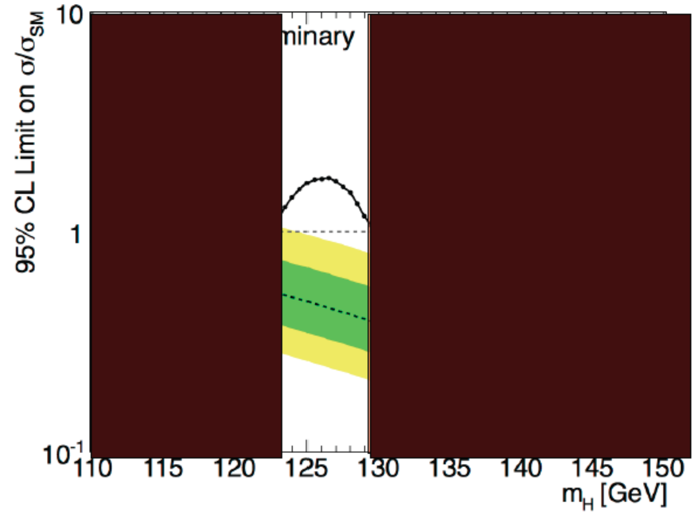


The Higgs mass in SUSY ?

$$M_S^2 = m_{q_3} m_{U_3} \geq (500GeV)^2$$

$$\boxed{M_{h^0}^2 = M_Z^2 \cos^2 2\beta + \frac{3M_t^2 h_t^2}{4\pi^2}\left(\ln\left(\frac{M_S^2}{M_t^2}\right) + \delta_t\right) + \cdots \qquad \simeq 125\,GeV\,(LHC)}$$

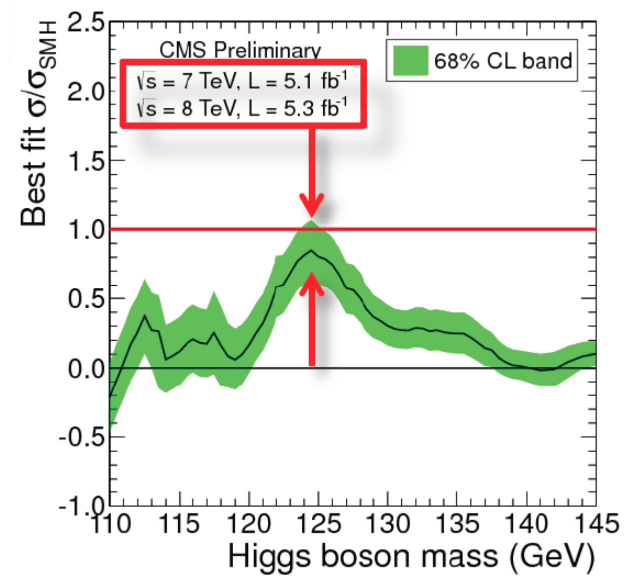
Atlas



Excluded at 95% CL

110-122.7   129-557 GeV

CMS



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Fine Tuning measure:

$$\Delta(a_i) = \left| \frac{a_i}{M_Z} \frac{\partial M_Z}{\partial a_i} \right|,$$

$$\Delta_{\max} = Max_{a_i} \Delta(a_i)$$

Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

Fine Tuning measure:

$$\Delta(\gamma_i)=\left|\frac{\gamma_i}{M_Z}\frac{\partial M_Z}{\partial \gamma_i}\right|,$$

$$\Delta_{\max}=Max_{a_i}\Delta(\gamma_i)$$

Ellis, Enquist, Nanopoulos, Zwirner

Barbieri, Giudice

Likelihood:

$$\delta\left(\mathrm{v}-\left(\frac{m^2}{\lambda}\right)^{1/2}\right)$$

$$L(\mathrm{data}|\gamma_i^0)=\frac{1}{\Delta_q}L(\mathrm{data}|\gamma_i;v_0,\beta,\tilde{y}_t(\beta),\tilde{y}_b(\beta))\Big|_{\beta=\beta_0(\gamma_i);\gamma_i=\gamma_i^0}$$

$$\chi^2(\gamma_i)=-2\ln(L)=\chi^2_{old}(\gamma_i)+2\ln\Delta_q$$

Ghilencea, Ross

$$\boxed{\Delta_q=\Big(\sum_i\Delta^2_{\gamma_i}\Big)^{1/2}}$$

$$\Delta_q=100,\quad \delta\chi^2/d.o.f.\sim 1$$

$$\Delta_q=1000,\quad \delta\chi^2/d.o.f.\sim 1.5$$

$$\chi^2/d.o.f.=2\,(2.5),\quad P=3\,(0.6)\%$$

- The CMSSM

$$\mu_0, m_0, m_{1/2}, A_0, B_0$$

assume correlation between SUSY breaking parameters

The CMSSM

$\mu_0, m_0, m_{1/2}, A_0, B_0$

$$\begin{aligned} V &= m_1^2\,|H_1|^2 + m_2^2\,|H_2|^2 - (m_3^2\,H_1\cdot H_2 + h.c.) \\ &+ \frac{1}{2}\lambda_1\,|H_1|^4 + \frac{1}{2}\lambda_2\,|H_2|^4 + \lambda_3\,|H_1|^2\,|H_2|^2 + \lambda_4\,|H_1\cdot H_2|^2 \\ &+ \left[\frac{1}{2}\lambda_5\,(H_1\cdot H_2)^2 + \lambda_6\,|H_1|^2\,(H_1\cdot H_2) + \lambda_7\,|H_2|^2\,(H_1\cdot H_2) + h.c.\right] \end{aligned}$$

Minimisation conditions:

$$v^2 = -m^2/\lambda, \qquad 2\lambda\frac{\partial m^2}{\partial\beta} = m^2\frac{\partial\lambda}{\partial\beta}$$

$$\begin{aligned} m^2 &= m_1^2\cos^2\beta + m_2^2\sin^2\beta - m_3^2\sin 2\beta \\ \lambda &= \frac{\lambda_1}{2}\cos^4\beta + \frac{\lambda_2}{2}\sin^4\beta + \frac{\lambda_{345}}{4}\sin^2 2\beta + \sin 2\beta\,(\lambda_6\cos^2\beta + \lambda_7\sin^2\beta) \end{aligned}$$

$$\boxed{\Delta \equiv \max\left|\Delta_p\right|_{p=\{\mu_0^2, m_0^2, m_{1/2}^2, A_0^2, B_0^2\}}, \qquad \Delta_p \equiv \frac{\partial \ln v^2}{\partial \ln p}}$$

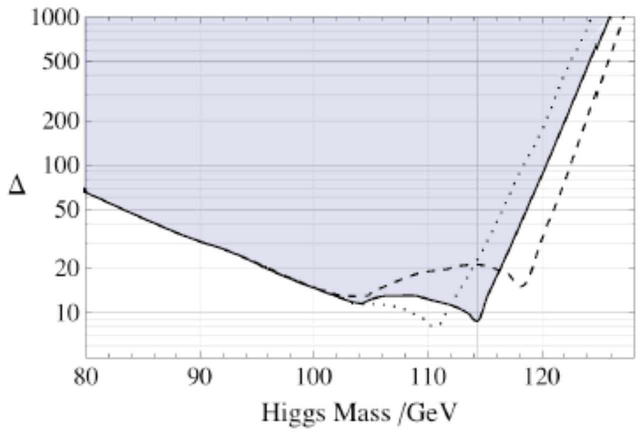
Couplings and masses evaluated to two loop (leading log) order

…enhanced sensitivity due to small tree-level $\lambda = \frac{1}{8}\left(g_1^2 + g_2^2\right)\cos^2 2\beta$

Cassel, Ghilencea, GGR
c.f. earlier work : Dimopoulos, Giudice
Chankowski, Ellis, Olechowski, Pokorski

• The CMSSM

$\mu_0, m_0, m_{1/2}, A_0, B_0$



Constraints

SUSY particle masses

$3.20 < 10^4\ \mathrm{Br}(b \to s\gamma) < 3.84$

$\mathrm{Br}(b \to \mu\mu) < 1.8 \times 10^{-8}$

$\delta a_\mu < 292 \times 10^{-11}$

$-0.0007 < \delta\rho < 0.0012$

Radiative EW breaking

Relic density unrestricted

$$\Delta \equiv \max \left|\Delta_p\right|_{p=\{\mu_0^2, m_0^2, m_{1/2}^2, A_0^2, B_0^2\}}, \qquad \Delta_p \equiv \frac{\partial \ln v^2}{\partial \ln p}$$

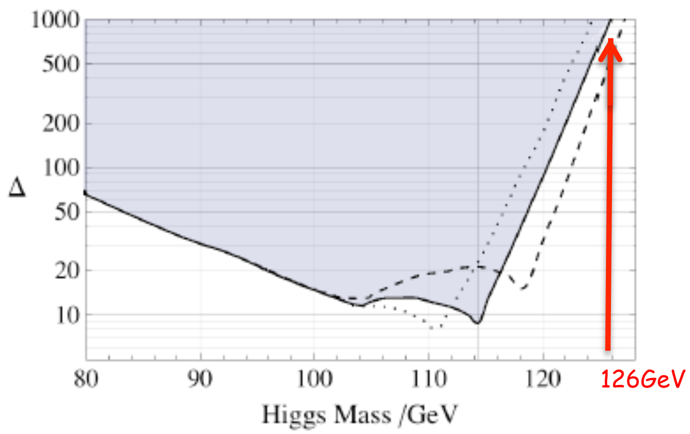
$$\boxed{\Delta_{Min} = 9, \quad m_h = 114 \pm 2 GeV}$$

(No Higgs bound applied)

• The CMSSM

$$\mu_0, m_0, m_{1/2}, A_0, B_0$$

...BUT



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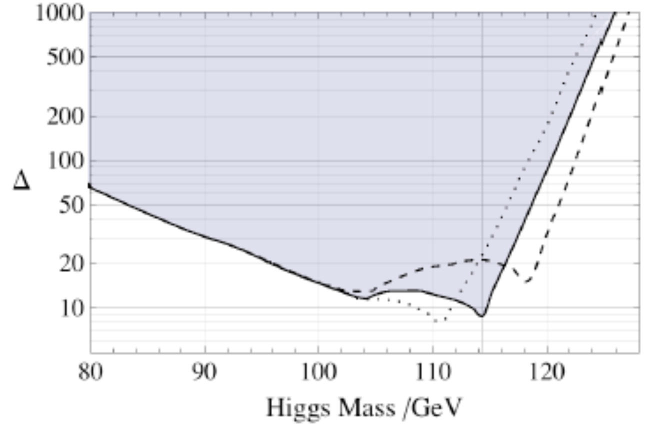

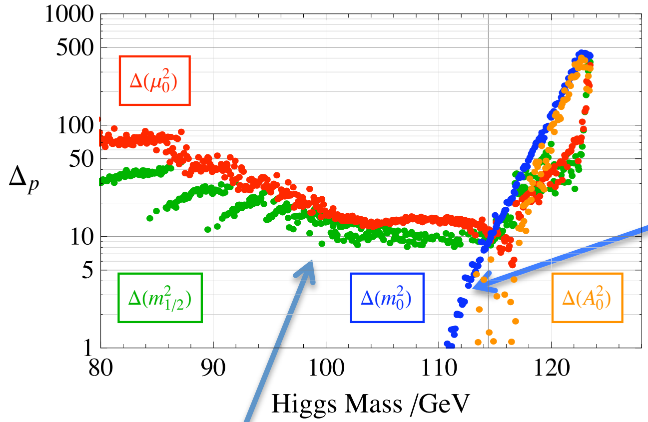

Limit of focus point

λ increase with m_H

Constraints

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Radiative EW breaking

Relic density unrestricted

$$v^2 = -\frac{m^2}{\lambda}$$

S.Cassel, D.Ghilencea, GGR

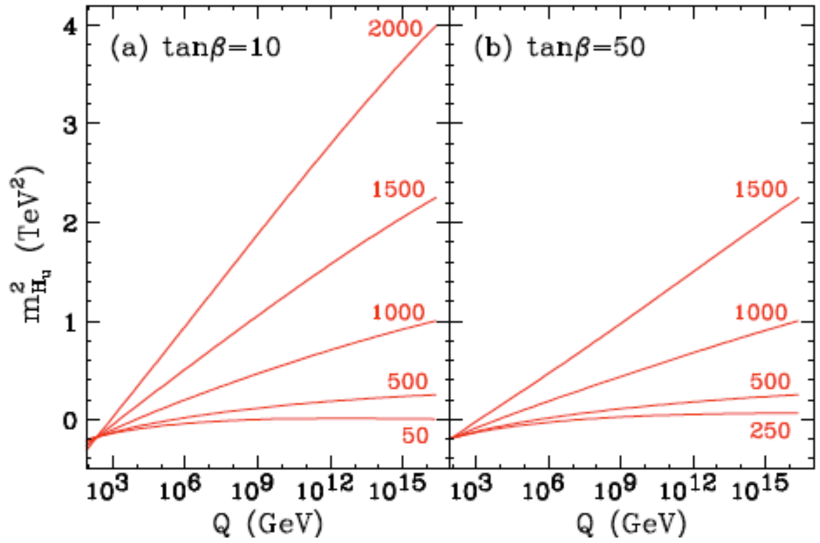
Focus Point

$$2|y_t|^2\,(m^2_{H_u}+m^2_{Q_3}+m^2_{\bar{u}3})+2|a_t|^2$$

$$16\pi^2\frac{d}{dt}m^2_{H_u}=3X_t-6g_2^2|M_2|^2-\frac{6}{5}g_1^2|M_1|^2$$

$$16\pi^2\frac{d}{dt}m^2_{Q_3}=X_t+X_b-\frac{32}{3}g_3^2|M_3|^2-6g_2^2|M_2|^2-\frac{2}{15}g_1^2|M_1|^2$$

$$16\pi^2\frac{d}{dt}m^2_{\bar{u}3}=2X_t-\frac{32}{3}g_3^2|M_3|^2-\frac{32}{15}g_1^2|M_1|^2$$



$$\boxed{m^2_{H_u}(Q^2)=\underbrace{m^2_{H_u}(M_P^2)}_{m_0^2}+\frac{1}{2}\underbrace{\left(m^2_{H_u}(M_P^2)+m^2_{Q_3}(M_P^2)+m^2_{\bar{u}3}(M_P^2)\right)}_{3m_0^2}\underbrace{\left[\left(\frac{Q^2}{M_P^2}\right)^{\frac{3y_t^2}{4\pi^2}}-1\right]}_{\simeq-\frac{2}{3},\ Q^2\simeq M_Z^2}}$$

"Focus point": $m^2_{H_u}(0)=m^2_{Q_3}(0)=m^2_{\bar{u}3}(0)\equiv m^2$

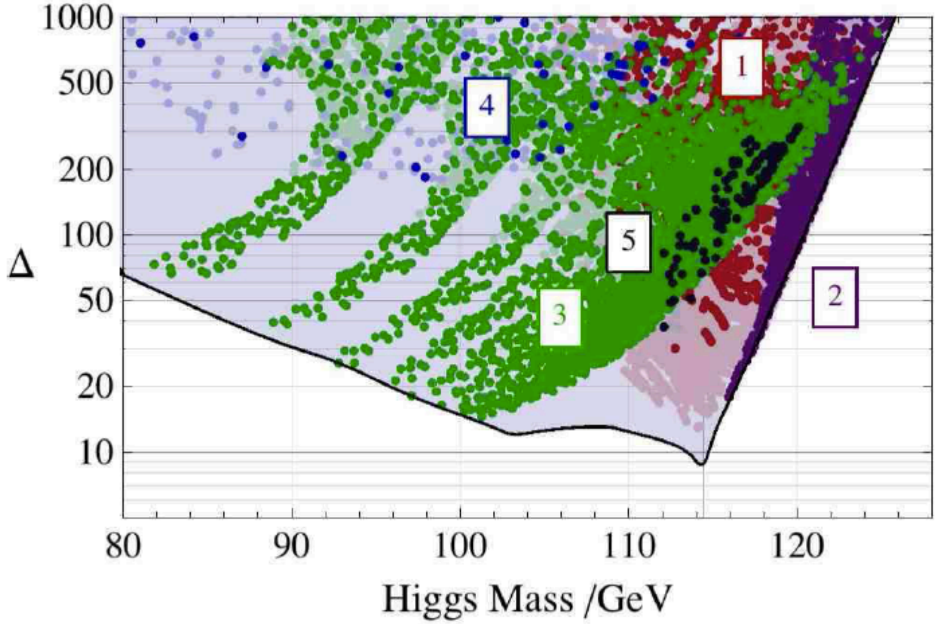
$$\boxed{m^2_{H_u}(t_0)=a_0\,m^2+..,\ a_0\leq 0.1}$$

Natural choice

$i.e.\ m^3_{Q_3}, m^2_{\bar{u}3}\gg M_Z^2$ possible

Feng, Matchev, Moroi
Chan, Chattopadhay, Nath
Barbieri, Giudice
Feng, Sanford

Dark Matter structure



Relic density restricted

1 h^0 resonant annihilation

2 $\tilde{h}$ t-channel exchange

3 $\tilde{\tau}$ co-annihilation

4 $\tilde{t}$ co-annihilation

• 5 A^0 / H^0 resonant annihilation

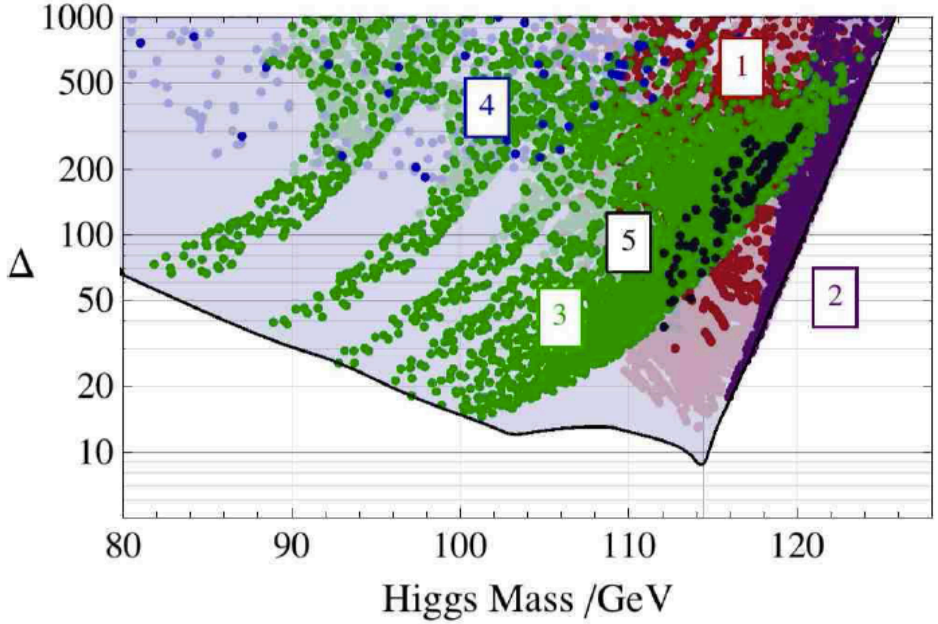
Within 3σ WMAP:

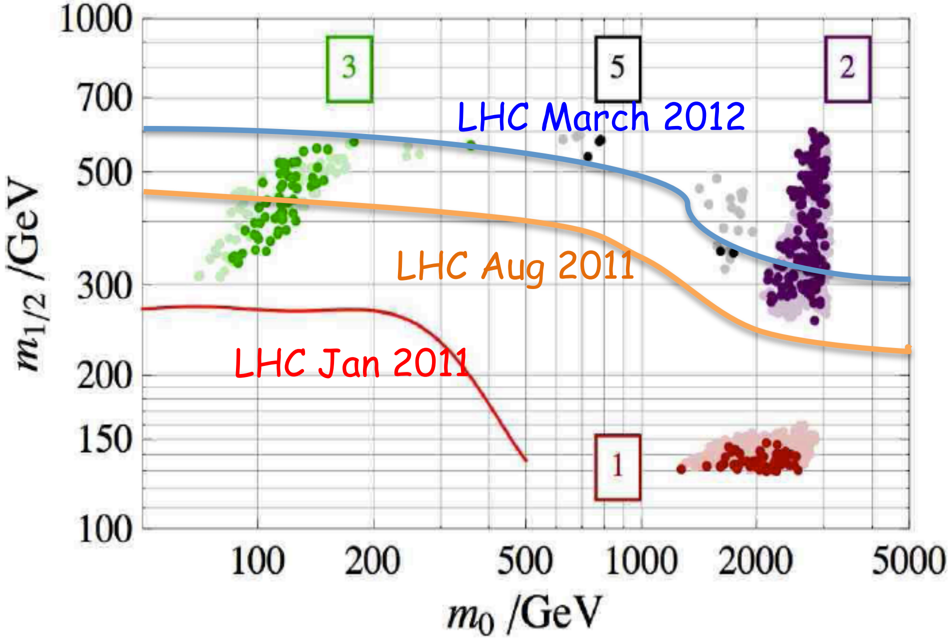
$\Delta_{Min} = 15, \quad m_h = 114.7 \pm 2 GeV$

< 3σ WMAP:

$\Delta_{Min} = 18, \quad m_h = 115.9 \pm 2 GeV$

Cassel, Ghilencea, GGR





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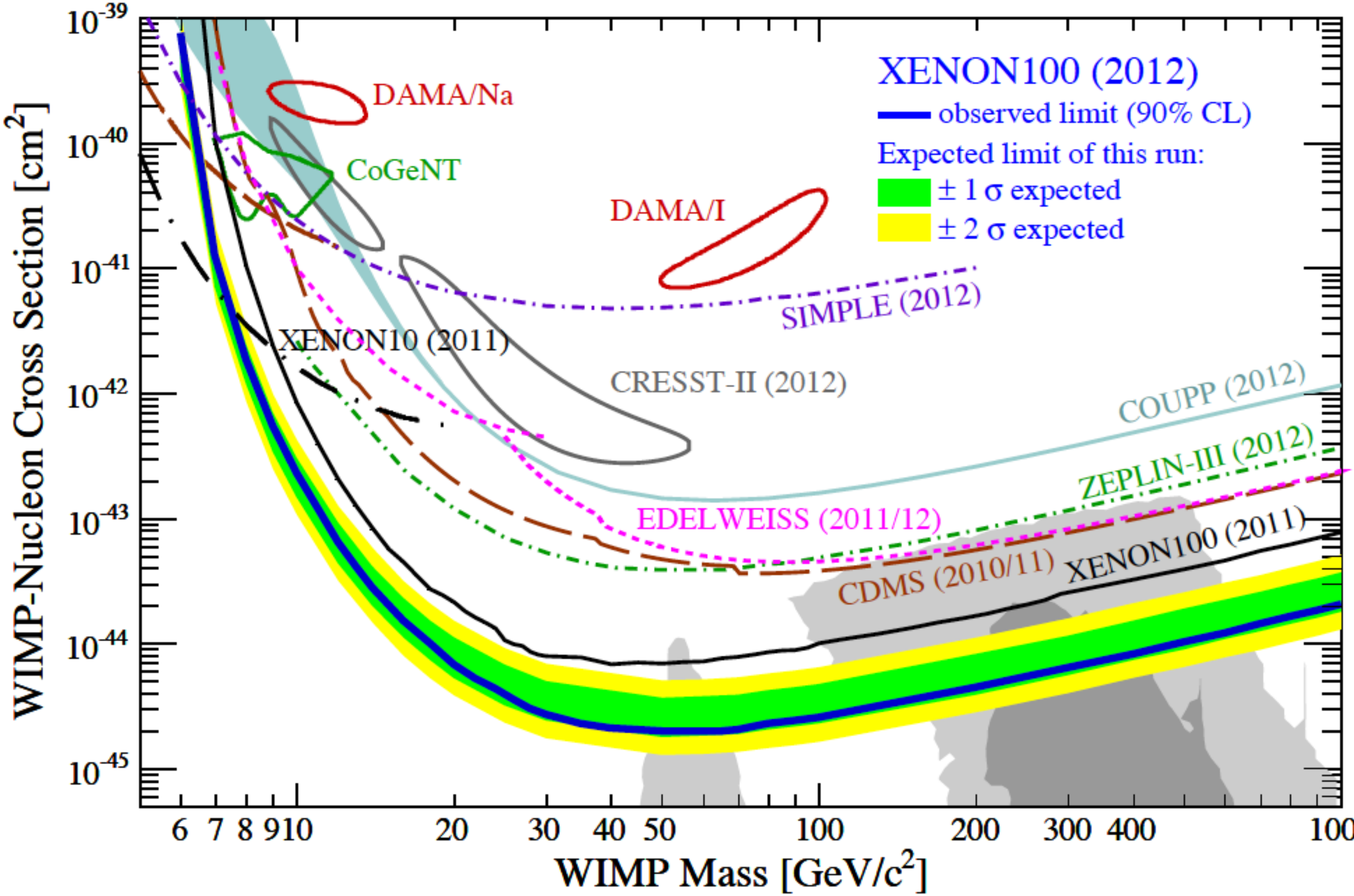
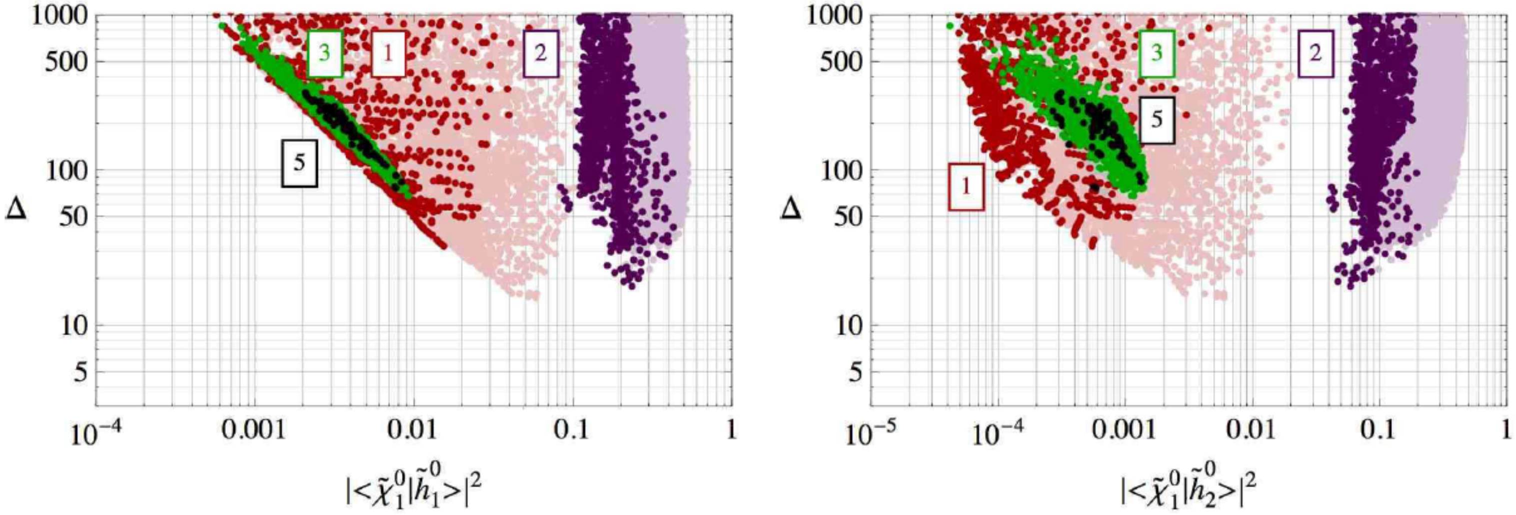
Cassel, Ghilencea, GGR

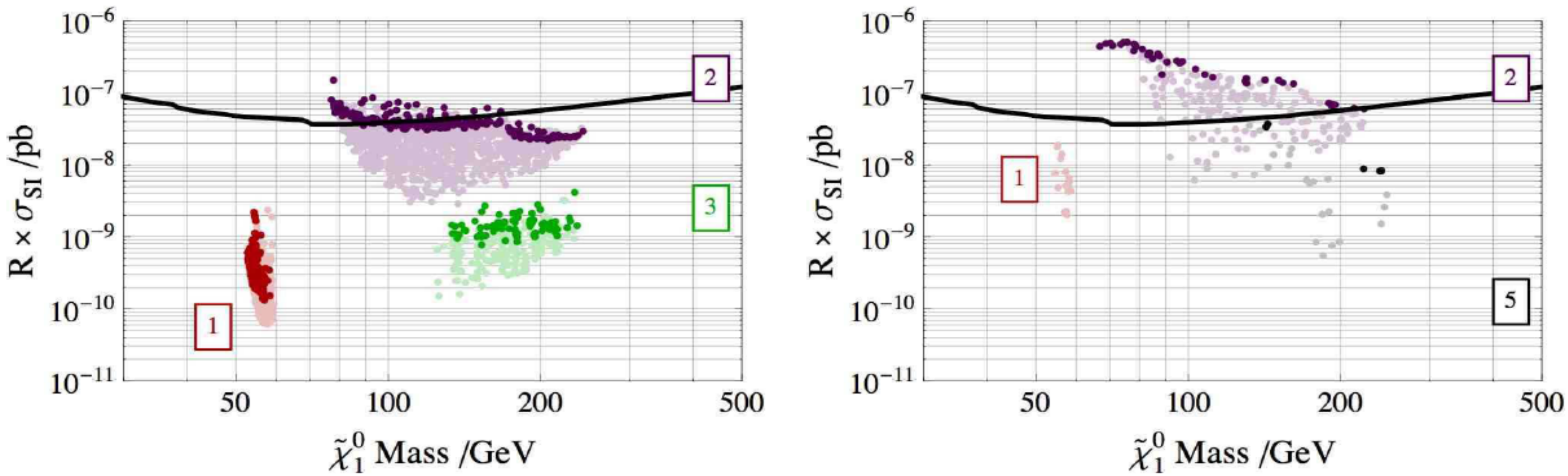
Direct dark matter searches: (spin independent)



DM - Scaled spin independent cross section for LSP-proton scattering:



(a) LSP $\tilde{h}_1^0$ component (b) LSP $\tilde{h}_2^0$ component



(a) $\tan\beta \leq 45$

$\Delta < 100$

(b) $50 \leq \tan\beta \leq 55$

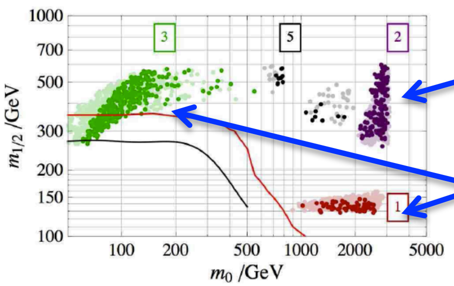
$\Delta < 100$

CMSSM summary:

- Minimises MSSM fine tuning (focus point) (c.f. gauge mediation $\Delta >> \Delta_{CMSSM}$)

$$Max\left[\Delta_{EW}, \Delta_{\Omega}\right] = 15(29), \quad m_h = 114(116) \pm 2GeV$$

- Complementary DM & LHC searches



(a) $m_h > 111$ GeV

DM $\quad \Delta \leq 100 \quad$ Sensitivity $\times (10-100)$ (Now achieved!)

LHC $\quad$ (Full region LHC $14TeV$ $10\,fb^{-1}$)

- *BUT* $\quad \Delta > 300$ for $m_H = 126GeV$

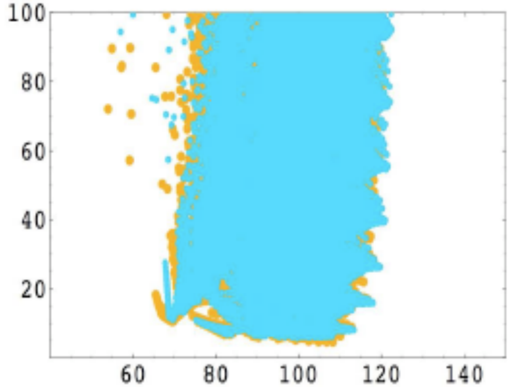
I. Reduced fine tuning : New heavy states - higher dimension operators

$$\delta L = \int d^2\theta \frac{1}{M_*}(\mu_0 + c_0 S)(H_1 H_2)^2 , \quad S = m_0 \theta\theta$$

Dimension 5

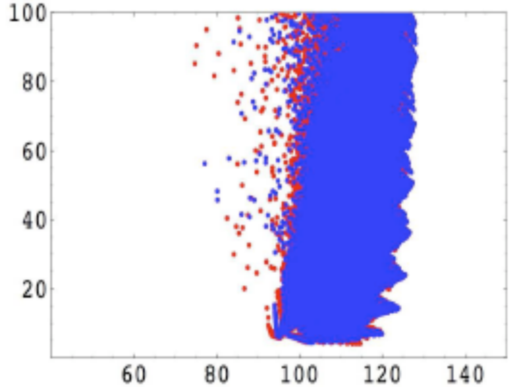
$$\delta V = \varsigma_1 \left(|h_1|^2 + |h_2|^2\right) h_1 h_2 + \varsigma_2 (h_1 h_2)^2 ; \quad \varsigma_1 = \frac{\mu_0}{M_*}, \ \varsigma_2 = \frac{c_0 m_0}{M_*}$$

Δ



m_h

MSSM



m_h

+ dim 5 operators

Cassel, Ghilencea, GGR
Casas, Espinosa, Hidalgo
Dine, Seiberg, Thomas
Batra, Delgardo, Tait
Kaplan,

Even for $M_*=65\ \mu_0$ a significant shift of m_h for constant Δ

…effect mainly comes from ς_1 term … origin?

Reduced fine tuning : singlet extensions

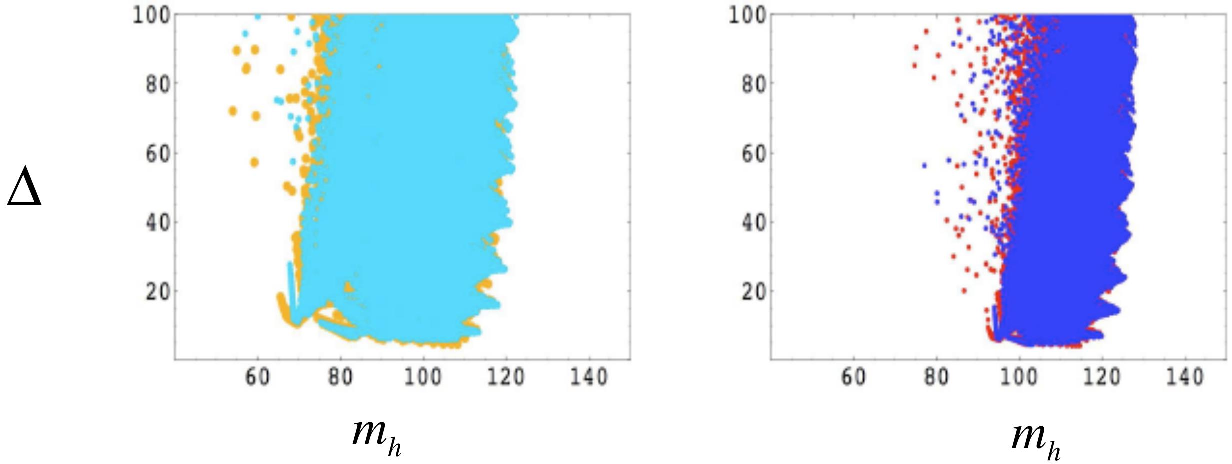
$$W = W_{\rm Yukawa} + (\mu + \lambda S) H_u H_d + \frac{\mu_S}{2} S^2 + \frac{\kappa}{3} S^3 + \xi S$$ GNMSSM

$\mu_S >> m_{3/2}$ †

$W_{eff}^{GNMSSM} = (H_u H_d)^2 / \mu_s + \mu H_u H_d$

c.f. $W = W_{\rm Yukawa} + \lambda S H_u H_d + \frac{\kappa}{3} S^3$ NMSSM

$\frac{\mu}{\mu_S}\left(|H_u|^2 + |H_d|^2\right) H_u H_d \rightarrow v^2 = -\frac{m^2}{\lambda}$



Reduced fine tuning in GNMSSM (but not NMSSM) †

SUSY extensions of the Standard Model

R-symmetry ensures Singlet extensions natural

SUSY extensions of the Standard Model

NMSSM spectrum
No perturbative μ term
Commutes with SO(10)
Anomaly cancellation

N	q_{10}	$q_{\bar{5}}$	q_{H_u}	q_{H_d}	q_S
4	1	1	0	0	2
8	1	5	0	4	6

R-symmetry ensures singlets light

D=5 operators

up and down Yukawas allowed

$$3q_{10} + q_{\bar{5}} + q_{H_u} + q_{H_d} = 4 \quad \text{Mod N} \quad \Rightarrow \quad 3q_{10} + q_{\bar{5}} = 0 \quad \text{Mod N} \quad \Rightarrow \quad \frac{1}{M}\cancel{QQQL} \quad \frac{1}{M}LLH_uH_u$$

Weinberg operator

SUSY breaking

$\langle W \rangle, \langle \lambda\lambda \rangle$ R=2 non=perturbative breaking

$Z^R_{4,8} \rightarrow Z^R_2 \quad R - parity$

Domain walls and tadpoles safe Abel

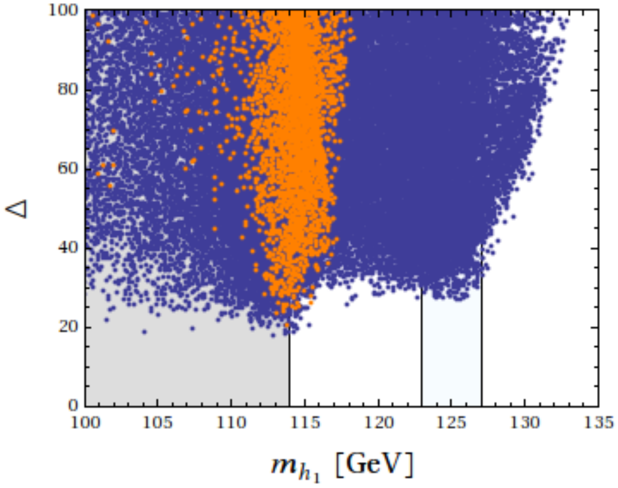
$\mu \sim m_{3/2}, \quad O(\frac{m_{3/2}}{M^2}QQQL)$

$$\boxed{\begin{aligned} W &= W_{MSSM} + \lambda S H_u H_d + \kappa S^3 + \Delta W \\ \Delta W_{Z_4^R} &\sim m_{3/2} H_u H_d + m_{3/2}^2 S + m_{3/2} S^2 \\ \Delta W_{Z_8^R} &\sim m_{3/2}^2 S \end{aligned}}$$

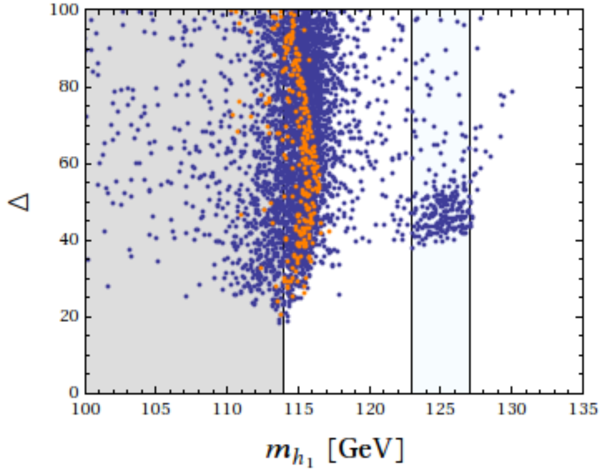
μ term and mass terms “natural”

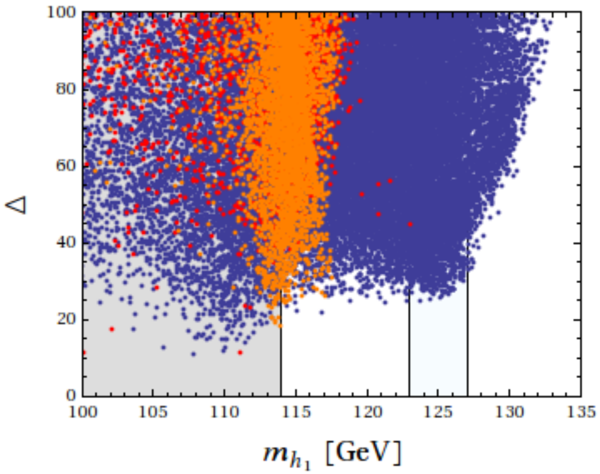
GNMSSM (c.f. NMSSM)

Fine tuning in the GNMSSM $(\lambda \leq 0.7^{\dagger})$

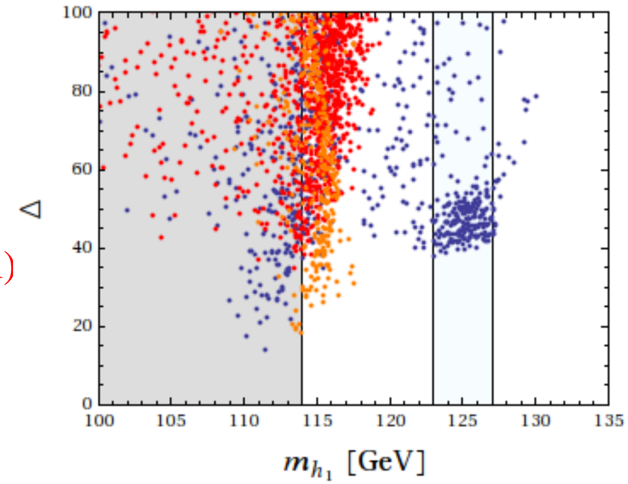


• CMSSM
• CGNMSSM
(universal masses)





• CMSSM
• CGNMSSM
• CNMSSM
(Higgs not universal)



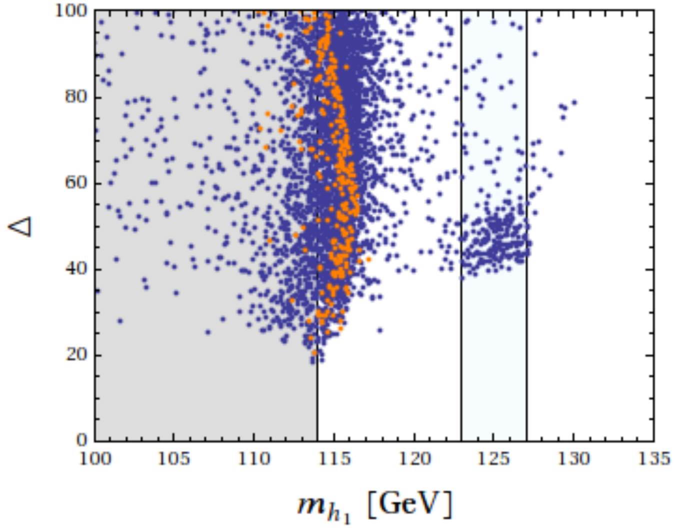
LHC constraints applied

LHC +DM constraints applied

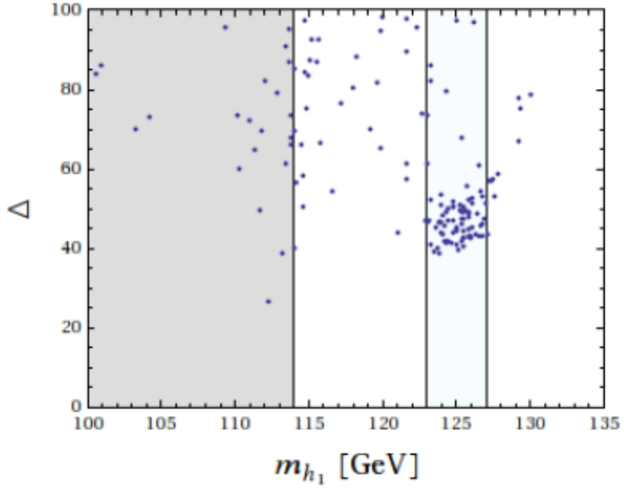
GGR, Schmidt-Hoberg , Staub

† c.f. Hall, Pinner, Ruderman

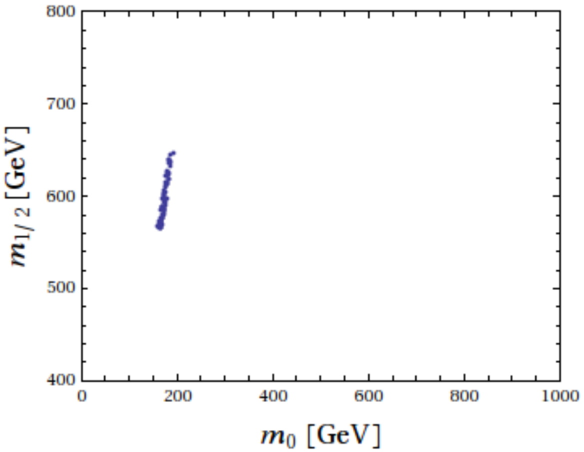
Dark Matter structure



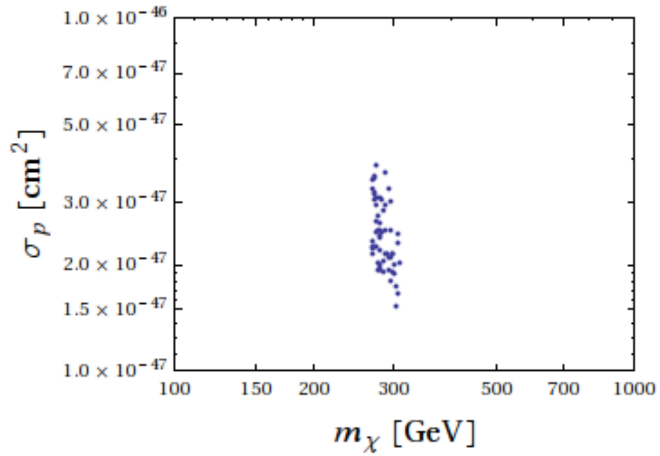
$\rho_{LSP} \leq \rho_{DM}$



$\rho_{LSP} \approx \rho_{DM}$



Stau co-annihilation



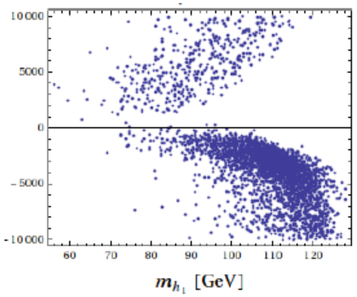
DM searches insensitive

GENERAL-NMSSM PHENOMENOLOGY

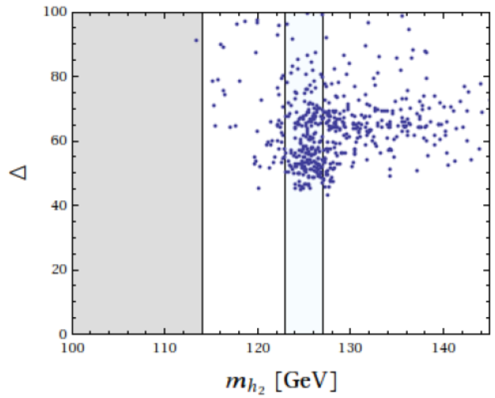
Higgs structure (h_u, h_d, s)

- $\mu_s \gg \mu$ MSSM SUSY structure with heavy Higgs

- $\mu_s, m_s, b_s \sim \mu$ $h_1 \simeq H_{u,d} + \varepsilon S, \quad h_2 = S - \varepsilon H_{u,d}$



$\ldots h_2$ may be lighter than LEP bound



m_{h_1} v/s Δ for the case $m_{h_2} < m_{h_1}$

Benchmark points

	BP1	BP2	BP3	BP4	BP5
m_0 [GeV]	746	163	957	573	752
$m_{1/2}$ [GeV]	476	568	557	482	472
$\tan\beta$	2.7	2.9	2.8	3.4	2.8
A_0 [GeV]	1433	1666	782	27	-198
λ	1.43	1.47	1.58	1.34	1.12
κ	-0.1	0.09	-0.005	1.52	1.03
A_λ [GeV]	A_0	A_0	A_0	400	192
A_κ [GeV]	A_0	A_0	A_0	-323	-326
v_S [GeV]	-841	-190	-929	390	281
μ_S [GeV]	-5931	-5354	-5799	131	-37
$m_{h_d}^2$ [GeV^2]	m_0^2	m_0^2	m_0^2	$9.1 \cdot 10^5$	$5.4 \cdot 10^5$
$m_{h_u}^2$ [GeV^2]	m_0^2	m_0^2	m_0^2	$2.3 \cdot 10^6$	$2.4 \cdot 10^6$
m_s^2 [GeV^2]	m_0^2	m_0^2	m_0^2	$2.8 \cdot 10^6$	$1.7 \cdot 10^6$
μ [GeV]	-750	-1136	-934	-33	10
$b\mu$ [GeV^2]	$-2.4 \cdot 10^6$	$-1.2 \cdot 10^6$	$-2.3 \cdot 10^6$	147	26
b_s [GeV^2]	$-1.9 \cdot 10^7$	$-5.4 \cdot 10^6$	$-1.4 \cdot 10^7$	326	144
ξ_s [GeV^3]	$2.2 \cdot 10^9$	$1.5 \cdot 10^9$	$3.0 \cdot 10^9$	22	-8
m_{squark} [GeV]	1256-1293	1207-1263	1507-1548	1211-1248	1280-1315
$m_{\tilde{g}}$ [GeV]	1219	1389	1416	1242	1235
m_{h_1} [GeV]	124	123.5	125	93.5	78
m_{h_2} [GeV]	1002	856	1257	125	124
h_1 singletfraction	$\mathcal{O}(10^{-4})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-4})$	0.8	0.85
$\text{Br}(h \to \gamma\gamma)$	$2.29 \cdot 10^{-3}$	$2.28 \cdot 10^{-3}$	$2.2 \cdot 10^{-3}$	$2.5 \cdot 10^{-3}$	$2.66 \cdot 10^{-3}$
$\text{Br}(b \to s\gamma)$	$3.1 \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$	$3.3 \cdot 10^{-4}$
Δa_μ	$-7.8 \cdot 10^{-11}$	$-2.5 \cdot 10^{-10}$	$-5.4 \cdot 10^{-11}$	$1.7 \cdot 10^{-10}$	$8 \cdot 10^{-11}$
$\delta\rho$	$6.2 \cdot 10^{-5}$	$6.6 \cdot 10^{-5}$	$7.5 \cdot 10^{-5}$	$1.9 \cdot 10^{-4}$	$3.1 \cdot 10^{-4}$
$m_{\tilde{\chi}_1^0}$ [GeV]	229	270	168	99	70
$\tilde{\chi}_1^0$ singlinofraction	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-5})$	0.1	0.2
Ωh^2	7.5	0.10	7.4	0.017	0.11
$\sigma_p[cm^2]$	$2.8 \cdot 10^{-47}$	$2.2 \cdot 10^{-47}$	$6 \cdot 10^{-47}$	$1.2 \cdot 10^{-44}$	$1.3 \cdot 10^{-45}$
Δ (Fine-tuning)	34.9	51.0	51.8	44.9	52.7

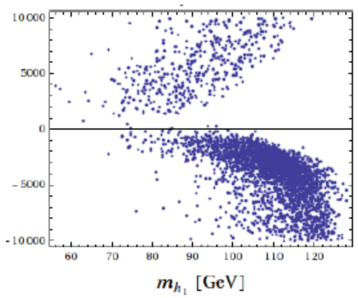
Table 1: Benchmark scenarios for the GNMSSM for the universal (BP1-BP3) and the general (BP4-BP5) case. m_{squark} shows the range of squark masses of the first two generations. For the last two points the second lightest Higgs is mostly MSSM-like.

GENERAL-NMSSM PHENOMENOLOGY

Higgs structure (h_u, h_d, s)

- $\mu_s \gg \mu$ MSSM SUSY structure with heavy Higgs

- $\mu_s, m_s, b_s \sim \mu$ $h_1 \simeq H_{u,d} + \varepsilon S, \quad h_2 = S - \varepsilon H_{u,d}$



...h_2 may be lighter than LEP bound $h_1 \to h_2 h_2$ large

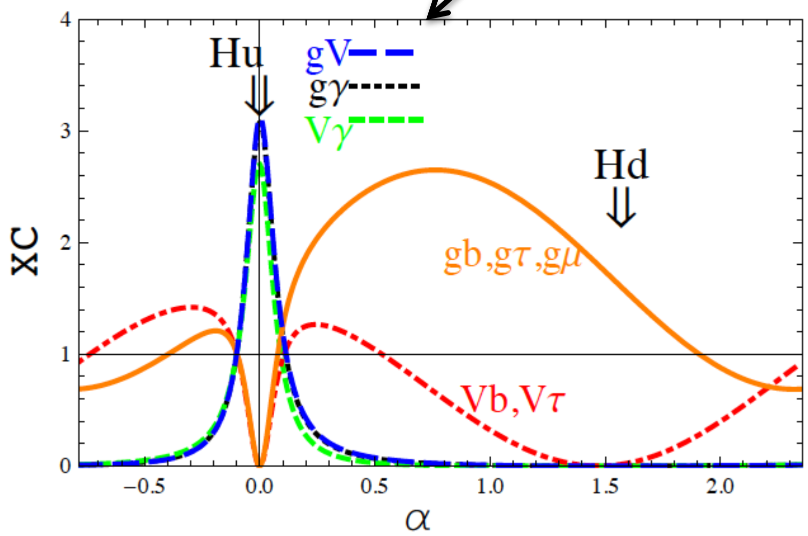
... DM and SUSY phenomenology modified e.g.Bino LSP

...h_1 may have enhanced $\gamma\gamma$ rate

$h \to \gamma\,\gamma$ enhancement in the MSSM

$g\gamma \equiv gg \to \gamma\gamma$ *etc*

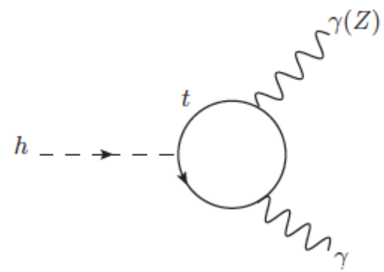
$$\frac{h}{\sqrt{2}} = c_\alpha H_u^0 - s_\alpha H_d^0$$



$\alpha \simeq 0$ fine tuned

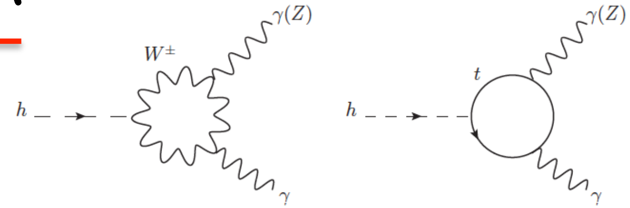
$$\left(M_H^2\right)_{12} = -(m_A^2 + M_Z^2)\sin\beta\cos\beta + \text{Loop}_{12} = 0$$

	$\sigma_h/\sigma_{h_{SM}}$	FT($\alpha = 0$)	($\alpha = 0.06$)	CMS[2]	ATLAS[1]	Tevatron[11]
$VV \to \tau\tau$	$V\tau$	0	0.60			
$q\bar{q} \to Vb\bar{b}$	qb	0	0.60	$1.2^{+2.1}_{-1.9}$	$-0.8^{+1.8}_{-1.7}$	2.0±0.7
$gg \to \tau^-\tau^+$	$g\tau$	0	0.74	$0.63^{+1.00}_{-1.28}$	0.0±1.7	
$gg \to \gamma\gamma$	$g\gamma$	3.1	1.9	1.62±0.68	$1.6^{+0.8}_{-0.7}$	$3.4^{+3.1}_{-2.4}$
$gg \to WW^*$	gW	3.1	2.0	0.40±0.55	0.20±0.62	$0.0^{+1.0}_{-0.0}$
$gg \to ZZ^*$	gZ	3.1	2.0	$0.58^{+0.94}_{-0.58}$	$1.4^{+1.3}_{-0.8}$	
$VV \to \gamma\gamma$	$V\gamma$	2.7	1.6	$3.8^{+2.4}_{-1.8}$[2]		



$h \to \gamma\gamma$ enhancement in the MSSM

See Djouadi review



...

New heavy particle contributions:

$$\mathcal{L}_{\gamma\gamma} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \sum_i \frac{b_i e^2}{16\pi^2} \log \frac{\Lambda^2}{m_i^2} + \cdots$$

$$\left\{ \begin{array}{lll} b_{1/2} = \frac{4}{3} N_{c,f} Q_f^2 & \text{for a Dirac fermion ,} \\ b_1 = -7 & \text{for the } W \text{ boson ,} \\ b_0 = \frac{1}{3} N_{c,S} Q_S^2 & \text{for a charged scalar .} \end{array} \right.$$

Carena et al

SUSY: light $\tilde{\tau}$ $\quad (LEP : m_{\tilde{l}} > 100 GeV)$

$$A_{\gamma\gamma}^{SM} + \Delta A_{\gamma\gamma} \propto -13 - \frac{m_{\tilde{\tau}_2}^2}{6 m_{\tilde{\tau}_1}^2} \left(1 - \frac{m_{\tilde{\tau}_1}^2}{m_{\tilde{\tau}_2}^2} \right)$$

anomaly/mirage..?

requires $\tan\beta \sim 60, \quad \mu \geq 300 GeV, \quad m_{\tilde{\tau}} \sim 100 GeV$

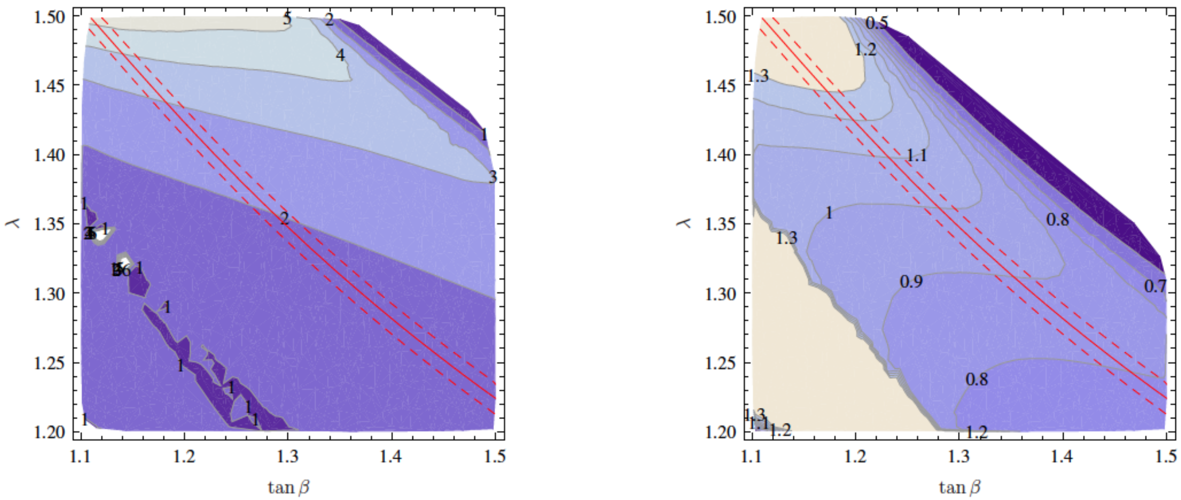
maximally mixed stau, heavy higgsinos, LSP light Bino

$h \to \gamma\gamma$ enhancement in the GNMSSM (λNMSSM)

New interaction allows sizeable correction at small tanβ:

$$W = \lambda S H_u H_d \quad \Rightarrow V \supset \lambda^2 \left| H_u H_d \right|^2$$

$$g_{hH^+H^-} = \frac{i}{4}\Big\{ v\cos\beta \Big[2(\lambda^2 - g_2^2) + (g_1^2 + g_2^2 - 2\lambda^2)\cos 2\beta \Big] Z_1^h$$
$$- v\sin\beta \Big[2(g_2^2 - \lambda^2) + (g_1^2 + g_2^2 - 2\lambda^2)\cos 2\beta \Big] Z_2^h$$
$$- 4\lambda \Big[v_s\lambda + \sqrt{2}\mu + (\tfrac{1}{\sqrt{2}}(A_\lambda + \mu_s) + v_s\kappa)\sin 2\beta \Big] Z_3^h \Big\}$$

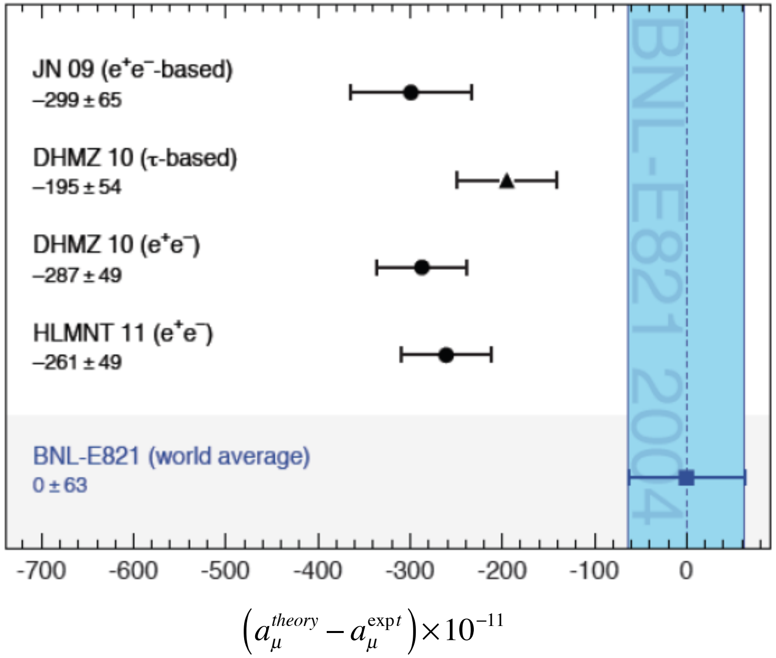


Higgsino (and chargino) enhancement in large λ limit

Schmidt-Hoberg, Staub

Muon g-2

$$\boxed{a_\mu^{theory} - a_\mu^{\exp t} = -(28.7 \pm 8.0) \times 10^{-10}}$$



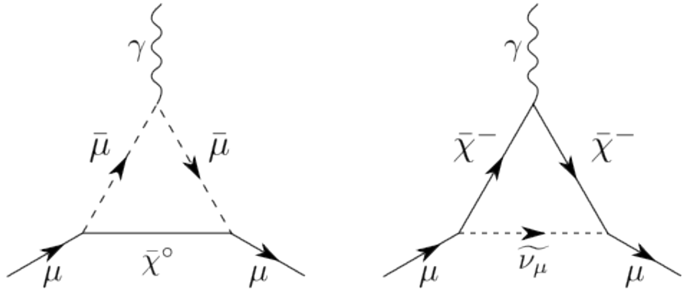
Theory error from hadronic contribution:

$$\delta a_\mu^{e^+e^-} = 3.6\,\sigma$$

$$\delta a_\mu^{\tau} = 2.4\,\sigma$$

SUSY

$$\delta a_\mu^{SUSY} = -13 \times 10^{-10} \left(\frac{100\,GeV}{M_{SUSY}}\right)^2 \tan\beta$$



Needs light sleptons – anomaly/mirage spectrum?

With slepton universality – $h \to \gamma\gamma$ plausibly correct!

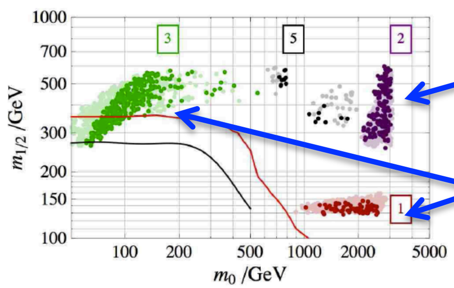
Giudice et al

Summary (before Higgs discovery)

- Hierarchy problem $\Longrightarrow$ SUSY breaking structure and/or further states

- CMSSM $m_i = M_0 \quad Max\left[\Delta_{EW}, \Delta_\Omega\right] = 15(29), \quad m_h = 114(116) \pm 2GeV$

  Complementary DM & LHC searches

  (a) $m_h > 111$ GeV

  DM $\quad \Delta \leq 100 \quad$ Sensitivity $\times (10-100)$

  LHC $\quad \left(\text{Full region } LHC \ 14TeV \ 10\,fb^{-1}\right)$

  (Gauge mediation $\Delta >> 100$)

- NMSSM Reduced Δ $\Longrightarrow$ GNMSSM $\Longrightarrow Z_{4R}, Z_{8R}$

  SUSY states can be (slightly)heavier

  $m_h \rightarrow 130GeV$

- Gaugino focus point $M_i = \eta_i M_{1/2}$

  Characteristic η_i

  Light $\chi^{0,\pm}$

  $\delta(b \to s\gamma)$ significant

  $\delta(g-2)$ Small(?)

Summary (after Higgs discovery)

- Hierarchy problem $\Longrightarrow$ SUSY breaking structure and/or further states

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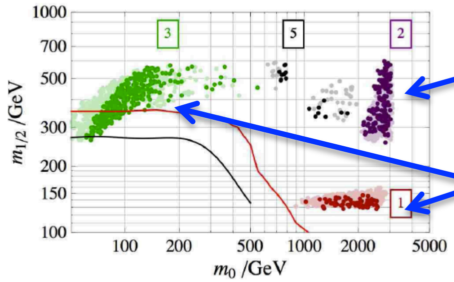


(a) $m_h > 111$ GeV

DM $\Delta \le 100 \quad$ Sensitivity $\times (10-100)$ (Now achieved!)

LHC $\left(\text{Full region } LHC \ 14TeV \ 10 fb^{-1}\right)$

$\Delta_{MSSM} > 300$ for $m_H = 126GeV$

- NMSSM Reduced $\Delta \Longrightarrow$ GNMSSM $\Longrightarrow Z_{4R}, Z_{8R}$

  Further light/invisible Higgs a possibility

- Gaugino focus point

  Mixed anomaly mediation, mirage mediation …

  Light sleptons…g-2, $h \to \gamma\gamma$

- Natural SUSY (but 125GeV Higgs?), SPLIT SUSY(!) …

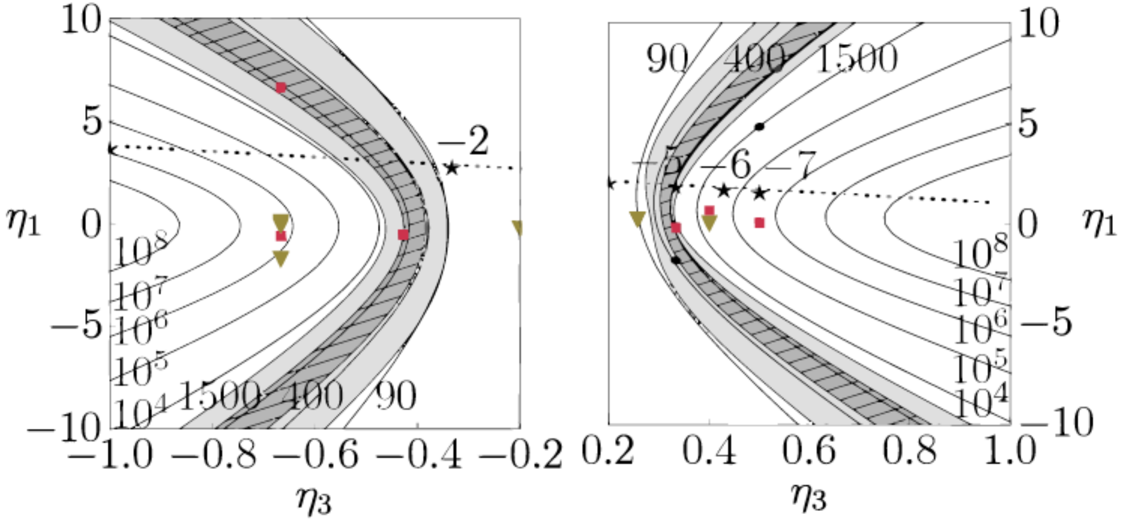
$$
\begin{aligned}
\frac{M_Z^2}{2} = \quad & -\,.87\,\mu^2(0) + 3.6\,M_3^2(0) - .12\,M_2^2(0) + .007\,M_1^2(0) \\
& -\,.71\,m_{H_U}^2(0) + .19\,m_{H_D}^2(0) + .48\,(m_Q^2(0) + \, m_U^2(0)) \\
& -\,.34\,A_t(0)\,M_3(0) - .07\,A_t(0)\,M_2(0) - .01\,A_t(0)\,M_1(0) + .09\,A_t^2(0) \\
& +\,.25\,M_2(0)\,M_3(0) + .03\,M_1(0)\,M_3(0) + .007\,M_1(0)\,M_2(0)
\end{aligned}
$$

II. Reduced fine tuning : nonuniversal gaugino masses

Reduced fine tuning : nonuniversal gaugino masses

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3\left(2\,|\,y_t\,|^2\,(m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}_3}^2) + 2\,|\,a_t\,|^2\right) - 6 g_2^2\,|\,M_2\,|^2 - \frac{6}{5} g_1^2\,|\,M_1\,|^2$$

New focus point: cancellation between M_3 and M_2 contributions if $|M_2|^2 \simeq |M_3|^2$ at M_{SUSY}



$$M_3 : M_2 : M_1 = \eta_3 : 1 : \eta_1$$

Reduced fine tuning : nonuniversal gaugino masses

$$16\pi^2 \frac{d}{dt} m_{H_u}^2 = 3\left(2|y_t|^2 (m_{H_u}^2 + m_{Q_3}^2 + m_{\bar{u}3}^2) + 2|a_t|^2\right) - 6g_2^2 |M_2|^2 - \frac{6}{5} g_1^2 |M_1|^2$$

New focus point: cancellation between M_3 and M_2 contributions if $|M_2|^2 \simeq |M_3|^2$ at M_{SUSY}

Natural ratios? e.g.:

GUT: $SU(5):\ \Phi^N \subset (24\times 24)_{symm} = 1+24+75+200;\quad SO(10):\ (45\times 45)_{symm} = 1+54+210+770$

$\eta_3 : 1 : \eta_1$ $\qquad\qquad$ $2.7\eta_3 : 1 : 0.5\eta_1$

Representation	$M_3 : M_2 : M_1$ at M_{GUT}	$M_3 : M_2 : M_1$ at M_{EWSB}
1	1:1:1	6:2:1
24	2:(-3):(-1)	12:(-6):(-1)
75	1:3:(-5)	6:6:(-5)
200	1:2:10	6:4:10

String: $(3+\delta_{GS}):(-1+\delta_{GS}):\left(-\frac{33}{5}+\delta_{GS}\right)$ (OII, also mixed moduli anomaly)

Phenomenology

- Gaugino mass ratios

$$\frac{M_i(Q)}{M_{1/2}} = \eta_i \frac{\alpha_i(Q)}{\alpha_i(M_X)} \quad \Rightarrow \quad \begin{aligned} &\frac{M_1(Q)}{M_2(Q)} \approx 0.5\eta_1 \\ &M_2(Q) \approx 0.8 M_{1/2} \\ &\frac{M_3(Q)}{M_2(Q)} \approx 2.7\eta_3 \end{aligned}$$

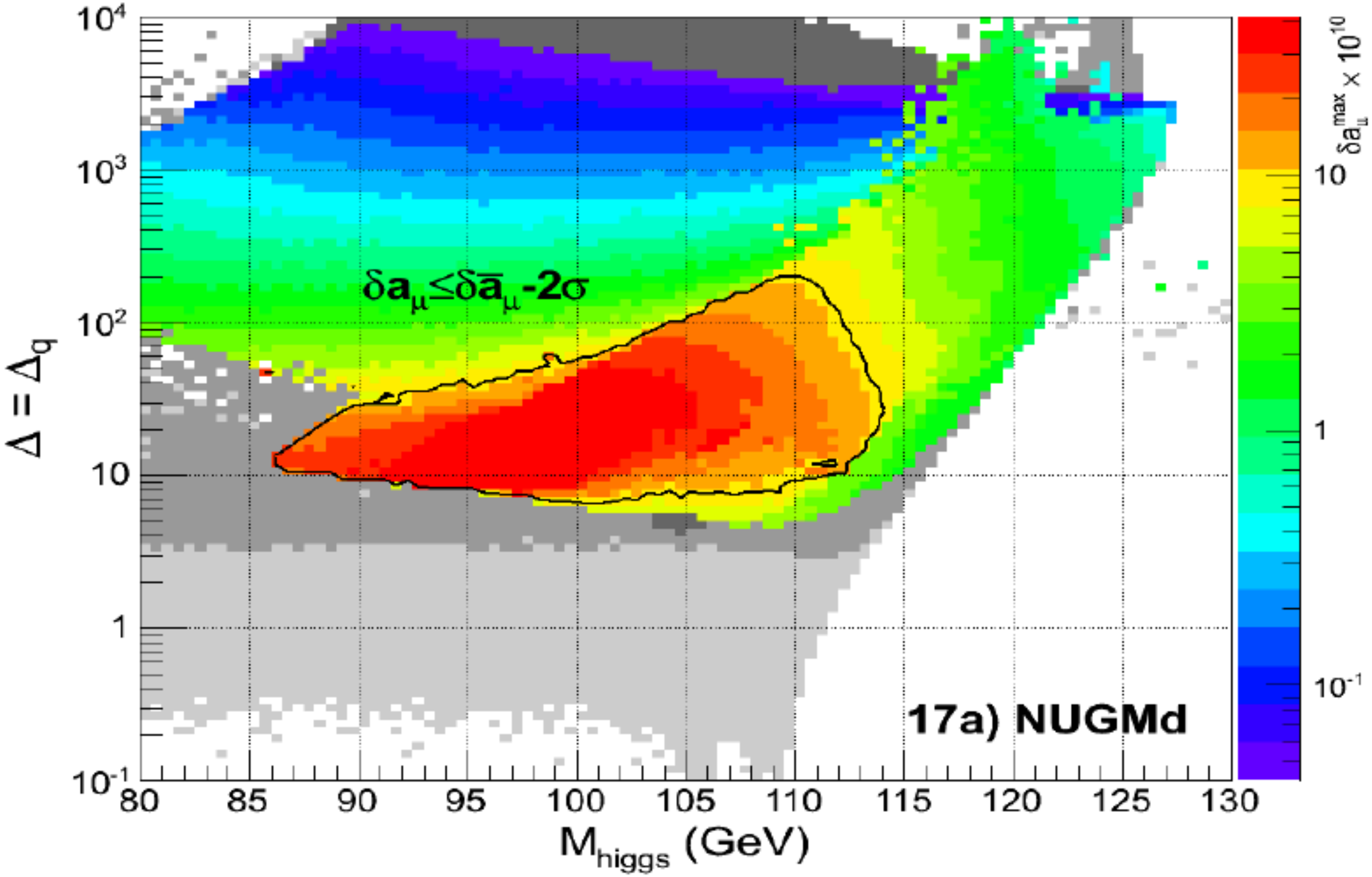
…. gauginos can be very heavy

- Light neutralino and 2 charginos nearly degenerate

$$m_{\chi_2^0} - m_{\chi_1^0} = M_Z^2 \left(\frac{s_W^2}{M_1} + \frac{c_W^2}{M_2} \right) + \mathcal{O}(\frac{M_Z^3}{M_2^2})$$

$$m_{\chi_1^\pm} - m_{\chi_1^0} = \frac{1}{2} M_Z^2 \left(\frac{s_W^2}{M_1} + \frac{c_W^2}{M_2} \right) + \frac{1}{2} M_Z^2 \left(\frac{s_W^2}{M_1} - \frac{c_W^2}{M_2} \right) \epsilon \sin 2\beta + \mathcal{O}(\frac{M_Z^3}{M_2^2})$$

$+ \text{ for } |M_1| < \mu,$ Bino or Higgsino LSP candidate



2-loop fine tuning in 75 case

Ghilencea, Lee, Park